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**SR 607**

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**EXPERIMENTAL EVALUATION OF THE  
APPARENT TEMPERATURE  
CONTRAST CREATED BY BURIED  
MINES AS SEEN BY AN IR  
IMAGER (U)**

BY

**J.R. SIMARD**



**NOVEMBER 1994**

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RALSTON, ALBERTA

SUFFIELD REPORT NO. 607

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### ABSTRACT

The detection of buried mines is a problem of prime interest internationally. One potential method to succeed in this task is to use passive IR imaging to form thermal images of the soil surface. Even though this technique has been intensively investigated for the last 15 years, only few publicly reported studies show quantitative measures of the apparent temperature contrast at the soil surface above buried mines. This document aims to improve this situation. Apparent temperature contrasts are measured for different mine-soil combinations over 24 hours periods with a camera sensitive to long wave infrared (8-12  $\mu$ m). The effect of the variation in burial depth is investigated and special attention is taken to differentiate the thermal effects associated with the soil disturbance from the mine itself. A maximum average of 2 degrees C in apparent thermal contrast is reported and this apparent thermal contrast disappears when the burial depth exceeds 8 cm for the case where the thermal disturbance is related to the buried mine only. A 50% increase ( $\sim$  3 degrees C) is observed when the thermal effect of the soil disturbance is present. Furthermore, this last apparent thermal contrast shows little dependency with the burial depth. These results are promising for the detection of mines buried in compacted soil. However, serious reservations about an acceptable false alarm rate and the duration of the thermal effect created by the soil disturbance are expressed.

### SOMMAIRE

La détection de mines sous la surface du sol est un problème mondial. Une méthode pouvant avoir un potentiel de succès implique l'analyse thermique de la surface du sol à l'aide d'une caméra infrarouge. Même si cette technique a été intensément étudiée durant les 15 dernières années, très peu de mesures quantitatives du contraste de la température apparente à la surface du sol créé par des mines ensevelies ont été rapportées. Ce document vise à améliorer cette situation. Une série de mesures de ce contraste apparent a été réalisée pour différentes combinaisons de mines et de types de sol durant des périodes de 24 heures à l'aide d'une caméra sensible aux longues longueurs d'ondes infrarouge (8-12  $\mu$ m). L'effet associé à la profondeur à laquelle la mine est enterrée a été analysé et une attention spéciale a été prise afin de différencier les effets thermiques reliés à la perturbation du sol de ceux reliés à la mine seulement. Un contraste maximum de la température apparente moyenne évalué à 2 degrés et disparaissant lorsque la mine est enterrée à une profondeur de 8 cm ou plus est rapporté lorsque l'effet thermique est associé à la mine seulement. Une augmentation de 50% ( $\sim$  3 degrés C) est observée lorsque l'effet thermique est associé à une perturbation du sol. De plus, ce contraste de la température apparente dépend très peu de la profondeur à laquelle la mine est enterrée dans ce dernier cas. Ces résultats sont prometteurs pour la détection de mines enterrées dans des sols compactés. Toutefois, de sérieuses réserves à propos d'un taux de fausses alarmes acceptable et de la durée de l'effet thermique créé par la perturbation du sol sont mentionnées.

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## ACKNOWLEDGEMENT

I would like to express my gratitude to Mr.Wayne Sirovyak who prepared the experimental set-up and wrote the data acquisition software. I would also like to thank him for kindly agreeing to spend nights on the tower to ensure that the experiment was carried out without interruption.

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# 1. Introduction

The detection of minefields has been a subject of strong interest for the last 40 years. This interest was primarily dictated by tactical considerations under a war scenario. But in the last 15 years, with the increase of peacekeeping activities in countries decimated by civil wars and other social disorders, the interest for mine detection (and clearance) has taken on even more importance. Many methods to perform this task have been proposed (imaging, magnetic, nuclear, vapor trace detection,...). However, one of the methods which has been researched actively since the early 70's is IR imaging. Recently, a few research groups from the United States (RECON/OPTICAL Inc. [2, 3], Wackenut Advanced Technology corp. [4], WES [5], ERIM [6]) have reported attractive capabilities in the detection of buried minefields with passive IR imaging systems. Furthermore, other NATO countries (UK, France) have also unofficially reported similar capabilities. Notwithstanding that such detection capabilities have been reported, little measurements have been performed (and published [7, 8, 9]) to evaluate quantitatively the apparent contrast in temperature that can be expected from buried mines when observed with an IR imager. The work done by Del Grande [7, 8] shows impressive results about the temperature contrasts of buried objects, filled holes and grass-covered sites with a dual-band IR imaging system. The work presented in this report aims to complete this research by evaluating the apparent temperature contrasts of buried mines over a 24-hour interval for different burial depths and types of soil. In addition, the thermal effect of disturbed soil is also investigated.

The structure of this report is as follows. In the first chapter, a simple theoretical basis to interpret qualitatively the thermal mechanisms involved in the behaviour of buried mines is shown. The second chapter presents the experimental results. These results describe the apparent temperature contrast at the soil surface where mines are buried. The measuring instrument is an IR camera (8-12  $\mu\text{m}$ ) and acquisitions are made over 24-hour periods. Furthermore, these acquisition periods are achieved for 3 types of anti-tank mine and 3 types of soil: top soil, clay, and masonry sand. Special attention is taken to differentiate between the case of a mine buried in undisturbed soil <sup>1</sup> and the case of a mine buried in disturbed soil. This last case refers to the situation where all the surrounding soil to the burial site is homogenized to eliminate the thermal effects associated with soil disturbance. Chapter 3 discusses the results of the experimental section. The thermal contrasts observed between different trials, the thermal mechanisms involved, and the false alarm rate problem are approached. Finally, Chapter 4 summarizes the principal observations reported in this document.

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<sup>1</sup>Relates to the situation where a hole is dug to bury the mine.

## 2. Theory

The heat transfer mechanisms dictating the thermal behavior of the soil surface during a 24-hour period are well known. In most cases, this thermal behavior is analyzed by defining the soil layer as a one-dimensional problem. This approach is acceptable for the case of buried mines <sup>1</sup> where the model is defined as two layers (see figure 2.1). In this model, the first layer represents the soil above the mine and the second represents the mine itself. With this structural model, differential equation(s) and boundary conditions originating from thermodynamic theory can be applied and solved for the particular problem of buried mines.

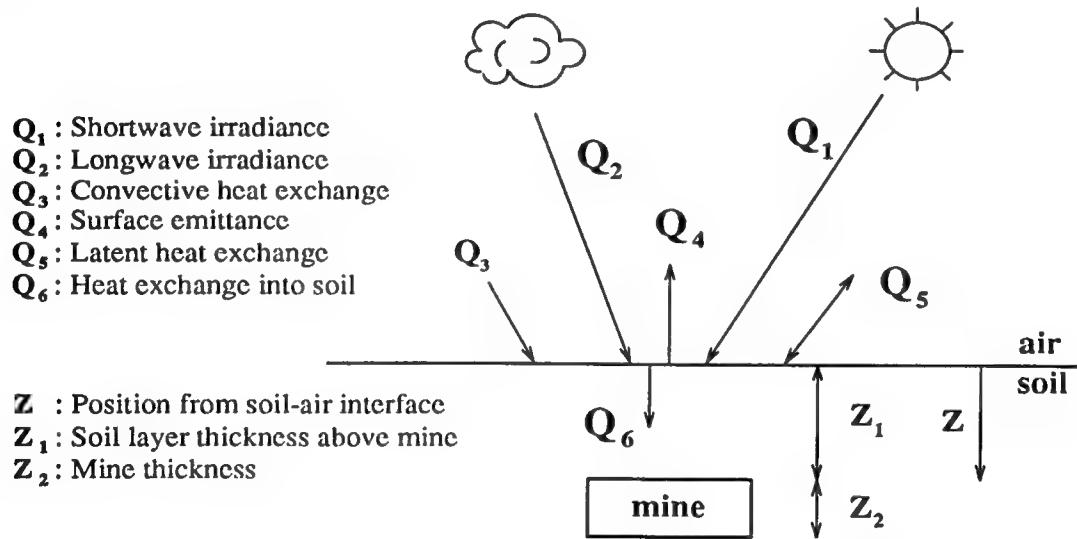


Figure 2.1: Schematic representation describing the thermodynamic model of a buried mine and its thermal interaction with the atmosphere. In this scheme, Q<sub>6</sub> represents the heat exchange with the soil underlayers and is modelled by the right side of equation 2.1.

The first differential equation historically [10] used to solve this kind of problem was the simple heat transport equation:

<sup>1</sup>This is not completely true for the situation where the burial depth has a dimension comparable to the lateral size of the area of interest above the mine. However, for the type of information that can be gathered realistically with this modeling technique, this one-dimensional approach is satisfactory.

$$\frac{\partial T(z,t)}{\partial t} = \kappa \frac{\partial^2 T(z,t)}{\partial z^2} + Q(z,t) \quad (0 \leq z \leq z_1 + z_2).$$

In this equation,  $T$  is the temperature,  $z$  is the vertical position,  $t$  is the time,  $\kappa$  is the thermal diffusivity (defined as the ratio between the thermal conductivity and the product specific heat  $\times$  specific mass) and  $Q(z,t)$  is the total heat source present at the position  $z$  and time  $t$ . It is with this type of differential equation that results were first obtained. Carslaw [11] presented an analytical solution of this classical heat conduction equation for a semi-infinite solid conductor with a sinusoidal temperature variation at its surface. His results predict that the amplitude of the "thermal wave" inside the solid follows an exponential decay with a penetration depth  $z_e$  equals to  $(P\kappa/\pi)^2$  where  $P$  is the period of the sinusoidal temperature variation. With this model and for most natural materials found in soils, this penetration depth is of the order of 10 cm for a 24-hour temperature variation period [9]. This result gives a first useful tool to figure out roughly the distance from the soil surface where atmospheric heat exchange changes have some thermal effects.

However, to obtain a more accurate insight in the thermal behavior of the soil surface, it is necessary to take into account that the soil is not an ideal solid but a porous material. This implies that the heat flow can be carried by moisture transfer (latent heat transfer) in addition to the classical conduction effect. To include this effect in the differential equation model describing the physics of heat transfer in soils, two combined differential equations, one for the heat flow conduction and the other for the moisture flow, have to be solved [12]. In one dimension, these equations are derived as [12, 13]

$$\left. \begin{aligned} \frac{\partial \Theta}{\partial t} &= \frac{\partial}{\partial z} \left\{ D_T \frac{\partial T}{\partial z} + D_\Theta \frac{\partial \Theta}{\partial z} + k_h \right\} \\ C_v \frac{\partial T}{\partial t} &= \frac{\partial}{\partial z} \left\{ K_T \frac{\partial T}{\partial z} + K_\Theta \frac{\partial \Theta}{\partial z} + k_h \rho_m h_m \right\} \end{aligned} \right\} \quad 0 \leq z \leq z_1 + z_2$$

with the following definitions:

- $\Theta$  : Moisture content,
- $\rho_m$  : Density of water,
- $h_m$  : Specific enthalpy of water,
- $k_h$  : Hydraulic conductivity,
- $C_v$  : Volume averaged heat capacity,
- $D_{T,\Theta}, K_{T,\Theta}$  : Nonlinear transport coefficients.

The first difficulty in the solution of this set of differential equations is embedded in the presence of non-linear and time dependent coefficients which are dictated by the soil properties, moisture content and temperature. General representations of the coefficients and other parameters of these equations can be found in the literature [14]. With this information, a numerical solution of these differential equations, even if complex, can be attempted. The second difficulty, which is associated with the boundary problem, is much

more difficult to solve. According to the definition of the model (see figure 2.1), three boundary conditions have to be satisfied:

1. Boundary between the soil and the bottom surface of the mine <sup>2</sup> ( $z = z_1 + z_2$ )

$$Q(z_1 + z_2, t) = 0 \quad \text{and} \quad e(z_1 + z_2, t) = 0$$

2. Boundary between the top surface of the mine and the soil ( $z = z_1$ )

$$\begin{aligned} \lim_{\epsilon \rightarrow 0} Q(z_1 - \epsilon, t) &= \lim_{\epsilon \rightarrow 0} Q(z_1 + \epsilon, t) \\ \lim_{\epsilon \rightarrow 0} e(z_1 - \epsilon, t) &= \lim_{\epsilon \rightarrow 0} e(z_1 + \epsilon, t) \end{aligned}$$

3. Boundary between the soil surface and the atmosphere ( $z = 0$ )

$$Q(0, t) = K_T \frac{\partial T}{\partial z} + K_\Theta \frac{\partial \Theta}{\partial z} + k_h \rho_m h_m \quad (2.1)$$

$$e(0, t) = D_T \frac{\partial T}{\partial z} + D_\Theta \frac{\partial \Theta}{\partial z} + k_h \quad (2.2)$$

In addition to the spatial boundary conditions, initial conditions have also to be satisfied. In most situation, this condition can be assumed to be an initial homogeneous temperature and moisture content:

$$\left. \begin{aligned} T(z, t) &= T_0 \\ \Theta(z, t) &= \Theta_0 \end{aligned} \right\} \quad [0 \leq z \leq (z_1 + z_2)] \cap t \leq t_0.$$

The major difficulty with these conditions is at the soil-atmosphere interface ( $3^{\text{rd}}$  boundary condition). A minimum series of five principal heat-exchange mechanisms included in  $Q(0, t)$  are identified at this interface:

- **Absorbed shortwave irradiance** ( $\lambda \leq 3 \mu\text{m}$ ). This is essentially the energy directly injected by the sun into the soil (diffuse or direct). Represented by  $Q_1$  in figure 2.1.
- **Absorbed longwave irradiance** ( $\lambda > 3 \mu\text{m}$ ). Because the sun has little emission in this band, this source of irradiance originates mostly from the sky and the surrounding terrain and becomes important at night. Represented by  $Q_2$  in figure 2.1.
- **Convective heat exchange.** This heat exchange is performed by the air movement above the soil surface and depends on the soil surface geometry, surrounding obstacles, and wind temperature and velocity. Represented by  $Q_3$  in figure 2.1.

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<sup>2</sup>For this condition, we usually assume that the mine is sufficiently deep that no heat or moisture flow ( $e(t)$ ) is exchanged.

Very sensitive	Moderately sensitive	Very insensitive
Air temperature	Relative humidity	Air pressure
Solar irradiance	Target height	Cloud cover (high)
Solar absorption coefficient	Wind speed	Time step
Thermal emission coefficient	IR sky irradiance	Thermal diffusivity
Top layer heat conductivity	Thermal conductivity	Grid spacing
Cloud cover (middle level)	Bottom boundary flux	
Cloud type		24-hr repetitions
Initial conditions		

Table I: Relative sensitivity of the thermodynamic model to several parameters as analyzed by Jacobs [1].

- **Surface emittance.** This mechanism represents the radiative emission of the soil surface because of its temperature. It is the mechanism which allows the monitoring of the temperature variation at the surface with the IR imager. Represented by  $Q_4$  in figure 2.1.
- **Latent heat exchange by condensation/evaporation.** This process includes principally the water condensation and evaporation created by dew and to a certain extent, the evaporation of rainfall. Represented by  $Q_5$  in figure 2.1.

This series of heat-exchange mechanisms, which is far from complete, introduces a large number of parameters (amount of high and low clouds, incident angle of sun rays, surrounding ground morphology, soil reflectivity,...). To make a direct and absolute model of the heat and mass transfer process, these parameters have to be evaluated empirically with sufficient precision. Usually, this task is almost impossible to perform without direct monitoring of the surface of interest. This limitation makes this model of little utility in precise thermal prediction of remote soils. However, this model introduces useful clues in the characterization of the relative importance of each of these parameters. This information could lead to a better understanding of the thermal variations observed in buried mines. Jacobs [1] studied the case of a concrete slab laying on the soil under clear and overcast conditions and after he carefully evaluated each parameter, he published the relative sensitivity of the model to several of them. These results are reproduced in Table I. Even if these results are associated with a concrete slab, it is believed that many results of this study are applicable to the case of buried mines.

To translate the results of Table I to the case of buried mines, it is important to realize that the detection of these buried mines with an IR imaging system is done by characterizing the local temperature contrast of the soil surface just above the buried mine compared to the immediate surrounding soil surface. This implies that many of the parameters listed in Table I (air temperature, solar irradiance...) which applied to large soil surface will have little effect in the local temperature contrast created by the buried mine in comparison to

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parameters which have a local impact (top layer heat conductivity, bottom boundary flux...). This concept should be kept in mind when conclusions presented in Table I are used to interpret general thermal mechanisms involved in the buried mines scenario.

### 3. Experimental Results

The previous chapter showed a theoretical model describing how buried mines can disturb the temperature uniformity of the soil surface. In this model, it was reported that a large number of empirical factors needs to be known with precision to reproduce the thermal variation of this soil surface with sufficient accuracy. Consequently, it has been decided to reproduce experimentally the situation where a soil layer covers mines and to monitor the thermal variations of the interface atmosphere-soil. This experimental verification will not specify precisely the thermal variations expected in all situations but what thermal variations can be observed. These observed experimental thermal variations will be presented in this chapter after the description of the experimental set-up used.

The simulation of the mine-soil compounds was performed with three types of anti-tank replica mines: the PM-60, the TMB-D, and the TMN-46<sup>1</sup>. Each of these replica mines has been filled with Uniroyal Adiprene, a plastic. This material has the particularity to closely simulate the thermal properties of the TNT without involving any explosive product. Each of these three types of mine was buried in three different types of soil: masonry sand, clay, and prairie top soil. For each mine-soil combination, four (three for the TMB-D) identical mines were buried at four different depths. These depths varied from 1 cm to 8 cm. The arrangement of the soil and the mines was done in a wood box with the following dimensions: 8' × 4' × 1.5' (~2.5m × 1.25m × 0.5m). These dimensions are sufficient to keep the distance between each mine and between the mines and the walls of the box to a value greater than the IR thermal diffusion length. Finally, it should be mentioned that each time the buried mines were interchanged from one type to one of the two others, the soil was mixed to minimize any inhomogeneity in density.

The wood box containing the buried mines was observed from a tower with an angle of view having a 25 degrees incline with the vertical. For each mine-soil combination, a 24-hour trial was carried out where IR images of the soil surface covering the buried mines were taken each 1/2 hour. The type of camera used was the Agema model AGA 782 with the following characteristics: long wavelength IR sensitivity (8-12  $\mu$ m), thermal sensitivity, as claimed by the manufacturer, of 0.1 °C, display resolution of 100 elements/line with 280 lines/frames (interlaced with 4:1 ratio), and a Field of View (FOV) of 3.5°x3.5°. With the distance camera-object plane at 15 meters, this FOV allowed the observation of the

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<sup>1</sup>Refer to Appendix A for a photograph of each of these mines.

soil surface without including the wooden border of the box. This configuration has the advantage of eliminating potential thermal inhomogeneities in the image and of reducing possible wrong thermal level settings associated with the auto-gain function of the camera. The calibration of the IR camera was done in laboratory with a thermally calibrated source.

The following figures show the apparent temperature contrast found for each trial. These apparent temperature contrasts were obtained by subtracting the average pixel reading of the image of the soil surface above the buried mines from the surrounding soil surface <sup>2</sup>. In addition, the air temperature <sup>3</sup> was sampled and the cloud cover conditions <sup>4</sup> were evaluated at regular intervals during the trial. This information is shown on a second graph for each trial. Unfortunately, the fixed orientation of the tower imaging facilities created a period during the 24-hour of acquisition cycle where the shadow of the tower passed over the wood box. The time of passage of the tower's shadow is about 1/2 hour and will be identified for each trial where sunlight is not negligible. Finally, two trials were specifically performed to verify the thermal behaviour of mines buried in real soil. These trials are named 'mines buried in undisturbed soil' to emphasize the fact that inhomogeneities in the soil are created when a hole is dug. To isolate this hole digging effect, one of the trial was done with mines buried in holes and the second trial was done with the same holes but without the mines. The analysis of these results are presented in the next chapter.

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<sup>2</sup>An image giving the precise position of each buried mine for each particular trial was taken. These pictures allowed the identification of the imaging pixels of the soil above the buried mines and these surrounding these areas.

<sup>3</sup>Temperature readings were done from a shadow corner shielded from the wind outside the shelter.

<sup>4</sup>These cloud cover conditions represent only a rough evaluation of the solar, cloud, and sky irradiation during the trial.

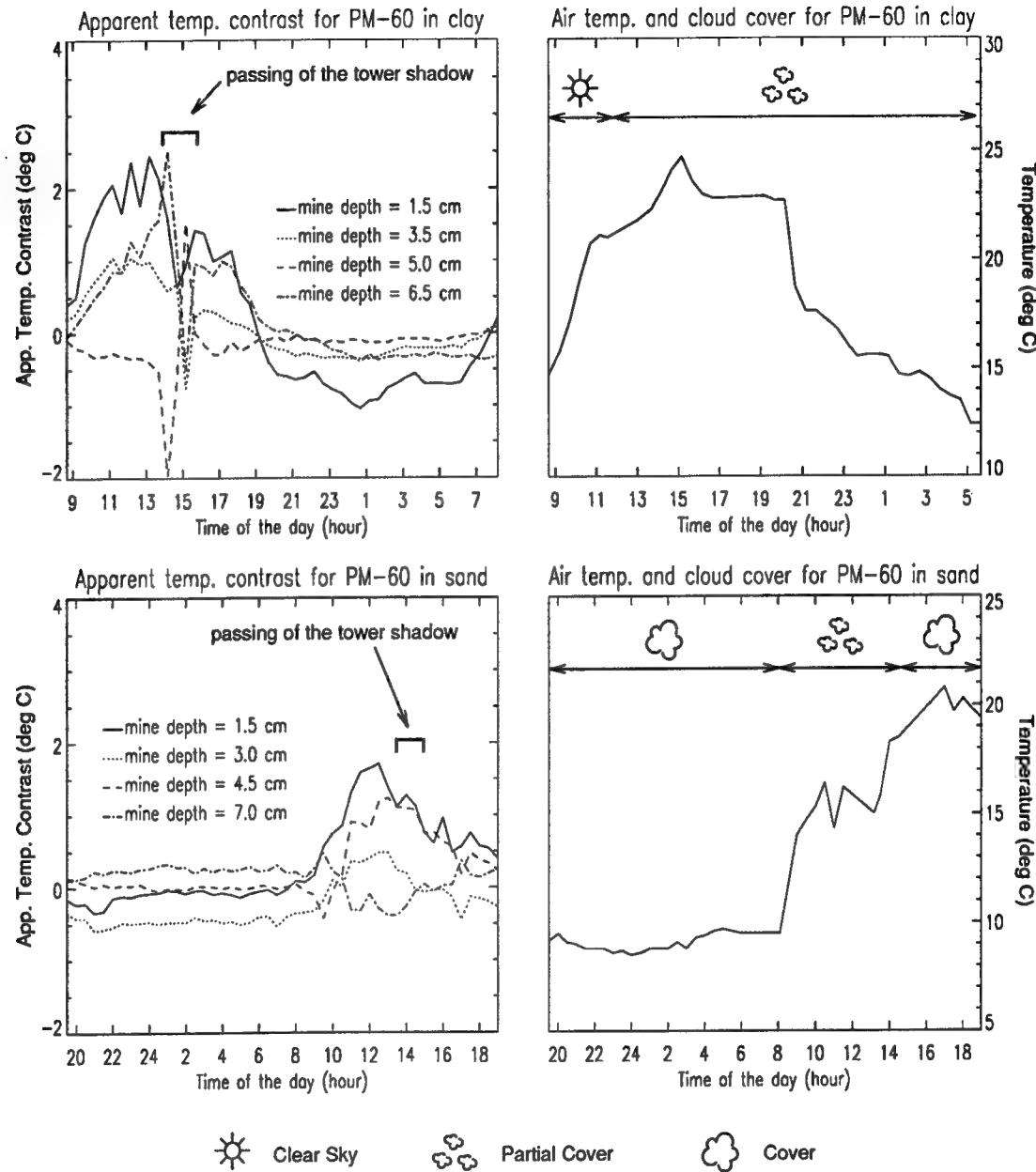


Figure 3.1: Apparent temperature contrast variation for the PM-60 replica anti-tank mine buried in clay and sand. The PM-60 and clay trial was performed August 18-19, 1993 and the mines were laid August 10, 1993. The PM-60 and sand trial was performed August 25-26, 1993 and the mines were laid August 25, 1993.

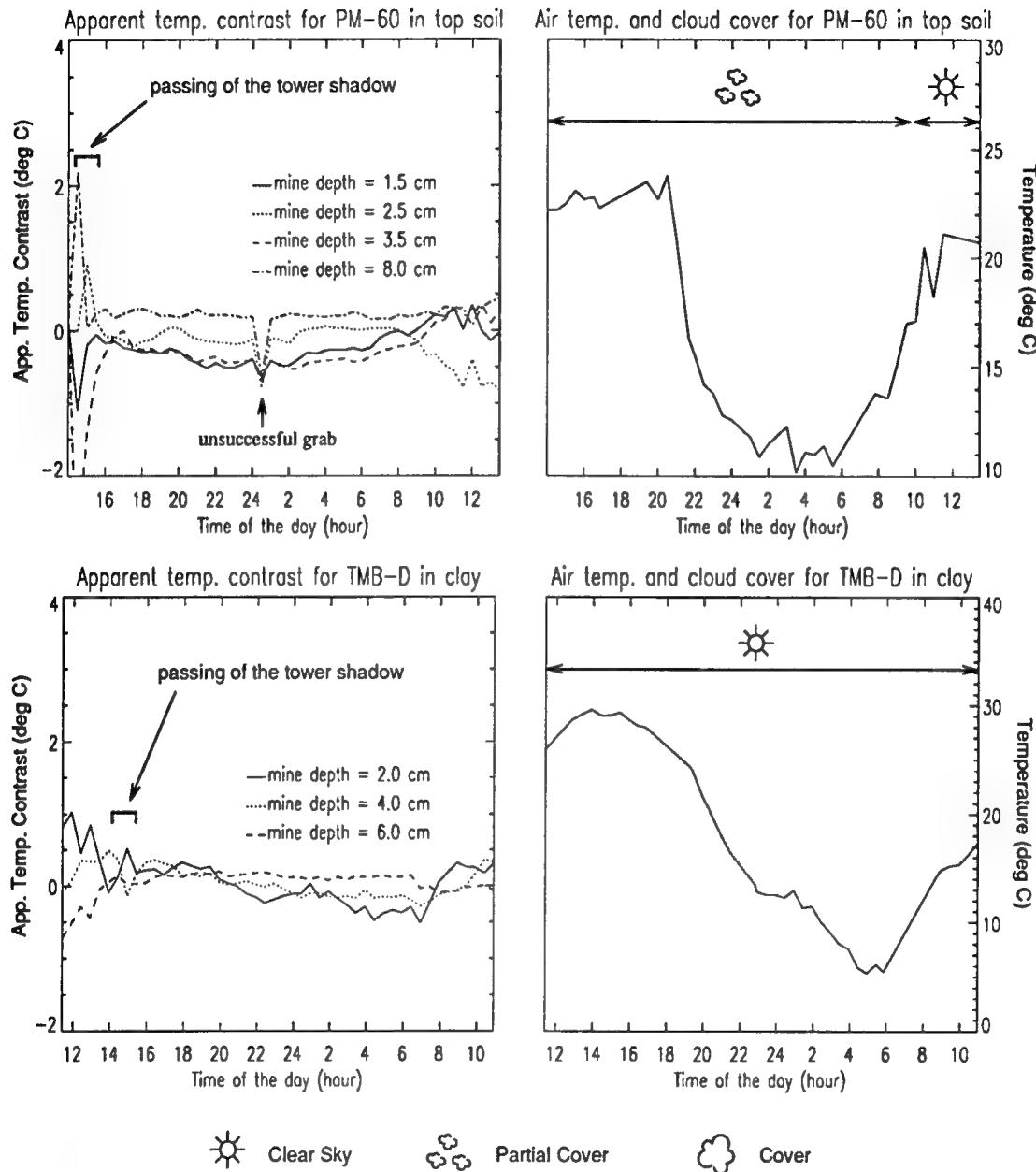


Figure 3.2: Apparent temperature contrast variation for the PM-60 replica anti-tank mine buried in prairie top soil and the TMB-D replica anti-tank mine buried in clay. The PM-60 and prairie top soil trial was performed July 21-22, 1993 and the mines were laid July 20, 1993. The TMB-D and clay trial was performed August 23-24, 1993 and the mines were laid August 23, 1993 at 09:00.

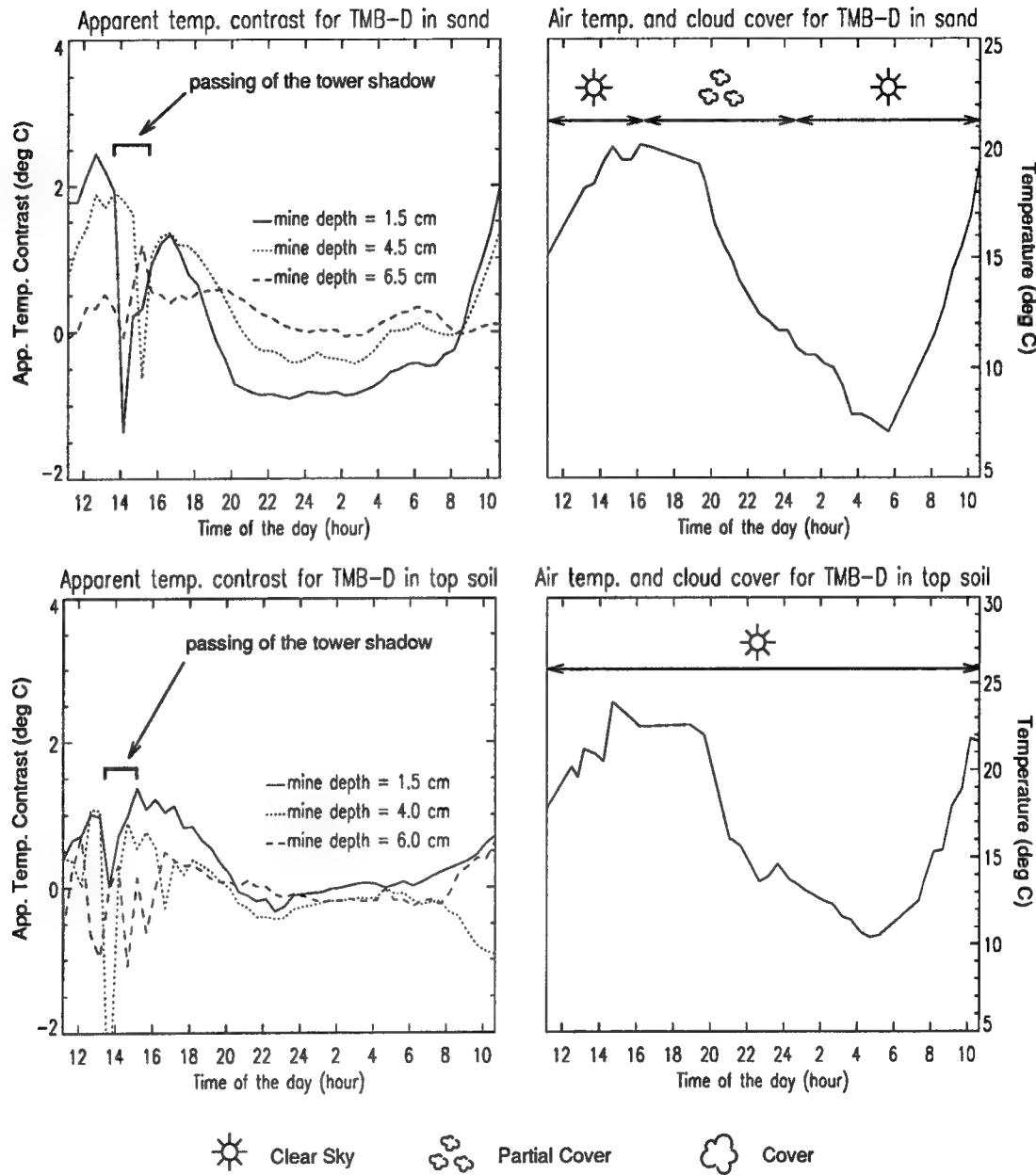


Figure 3.3: Apparent temperature contrast variation for the TMB-D replica anti-tank mine buried in sand and prairie top soil. The TMB-D and sand trial was performed August 30-31, 1993 and the mines were laid August 26, 1993. The TMB-D and prairie top soil trial was performed August 3-4, 1993 and the mines were laid August 2, 1993 at 16:30.

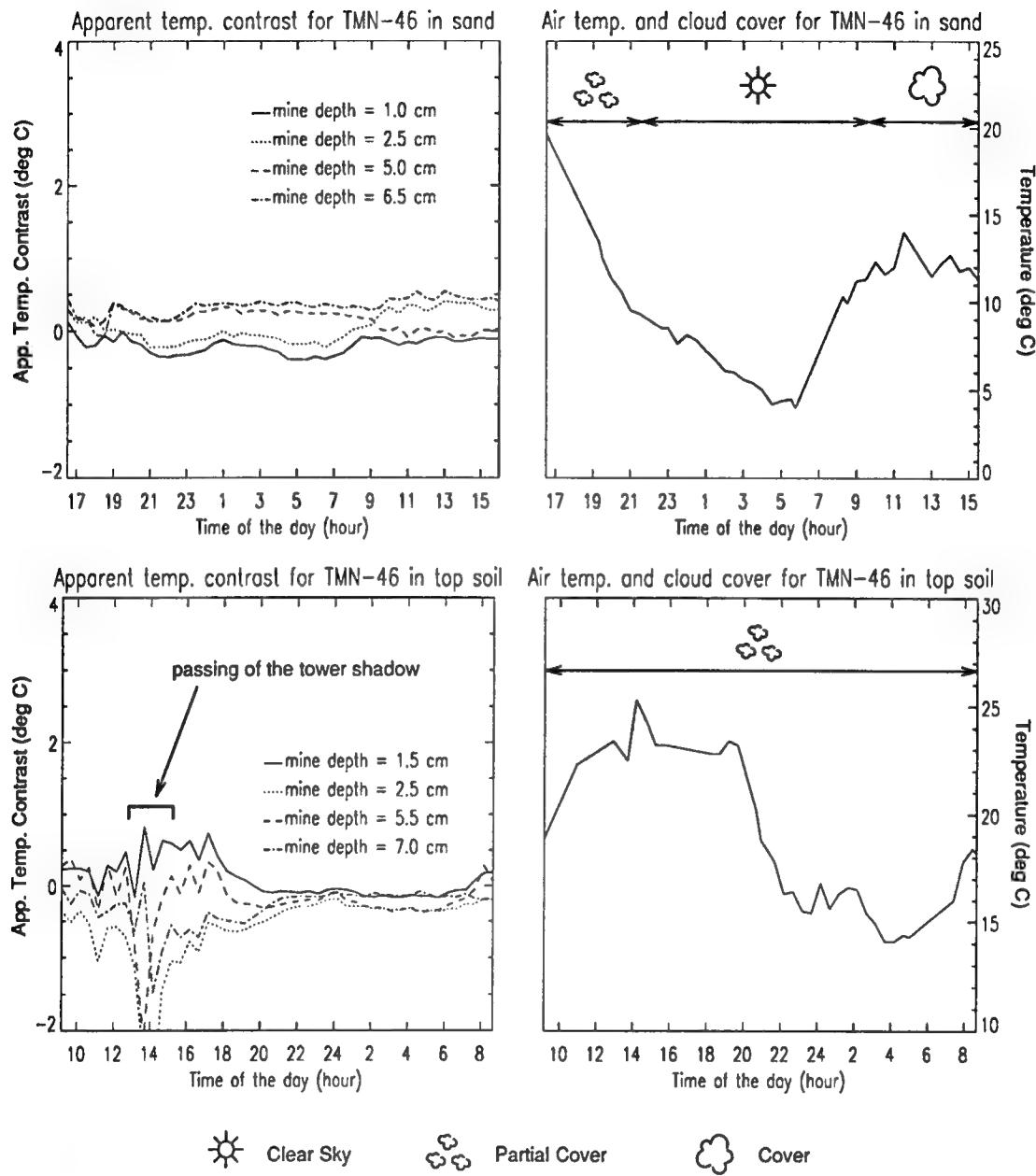


Figure 3.4: Apparent temperature contrast variation for the TMN-46 replica anti-tank mine buried in sand and prairie top soil. The TMN-46 and sand trial was performed August 24-25, 1993 and the mines were laid August 24, 1993 at 14:30. The TMN-46 and prairie top soil trial was performed July 19-20, 1993 and the mines were laid July 15, 1993.

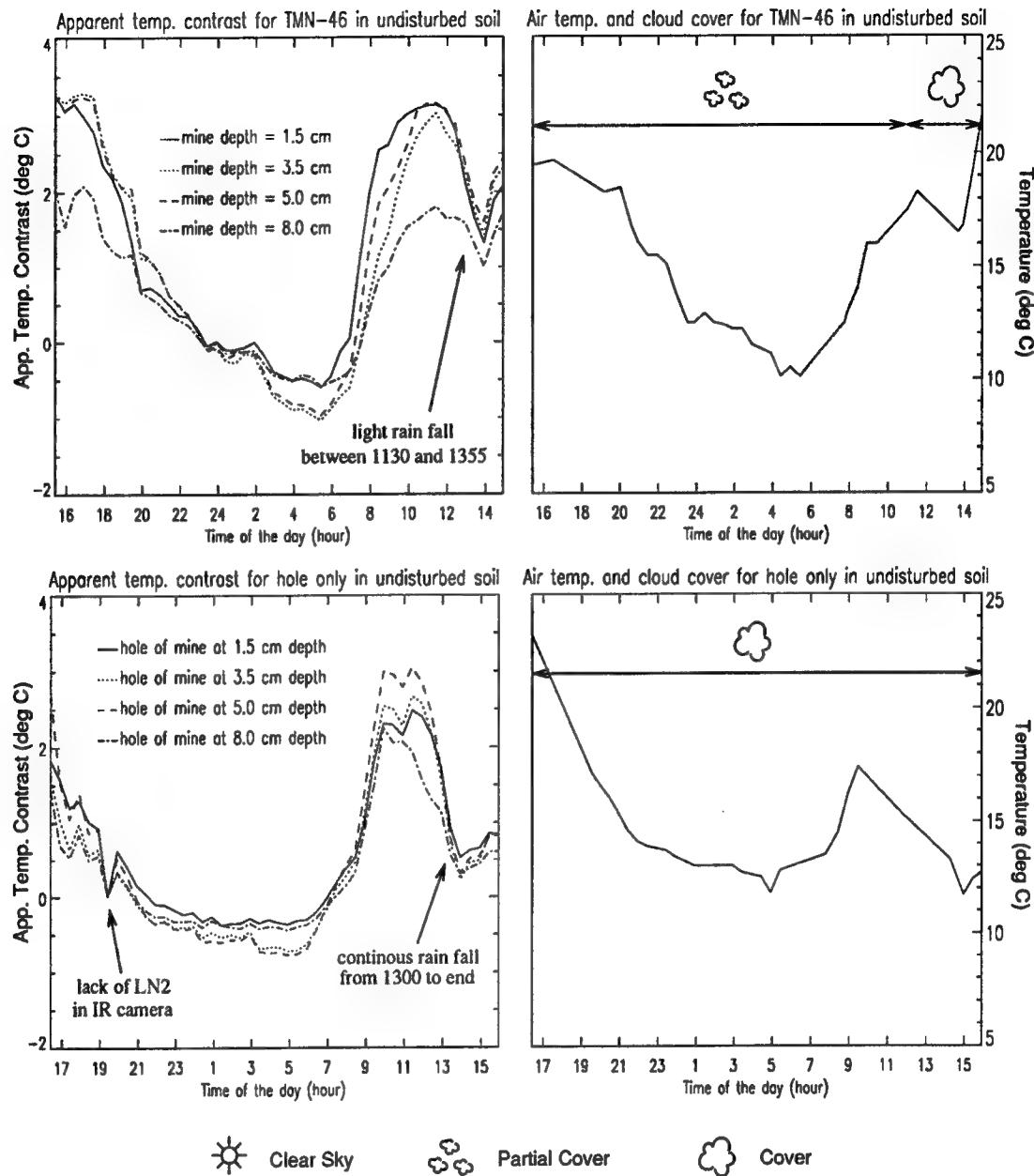


Figure 3.5: Apparent temperature contrast variation for the TMN-46 replica anti-tank mine buried in undisturbed soil and the apparent temperature contrast variation of the same holes but without the TMN-46 anti-tank mines. The buried site was grassless. The TMN-46 burial in undisturbed soil trial was performed July 5-6, 1993 and the mines were laid July 5, 1993 at 11:00. The hole only trial was performed July 6-7, 1993 and the arrangement of the soil was done July 6, 1993 at 16:00.

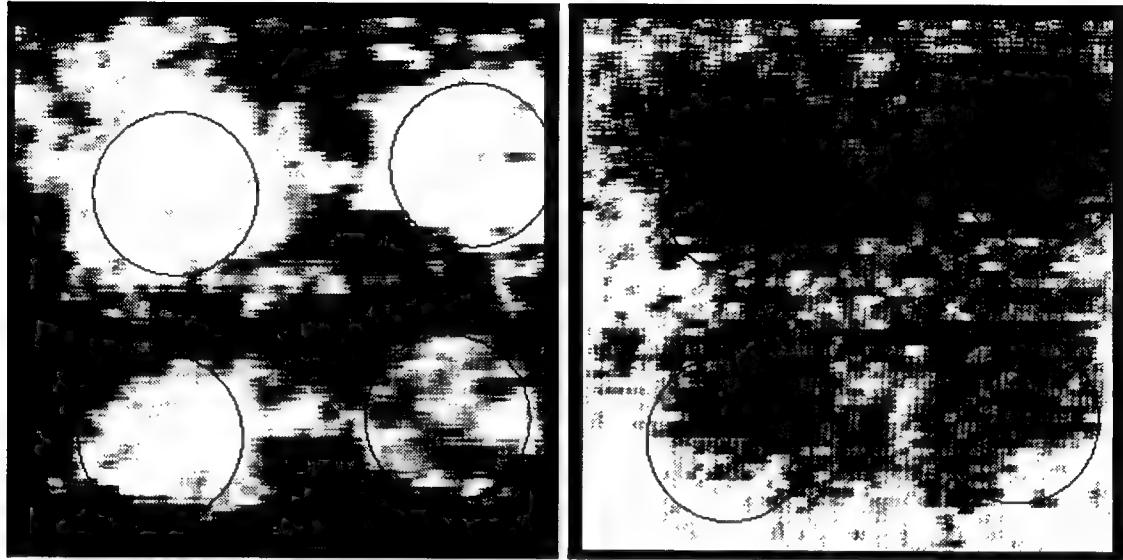


Figure 3.6: Apparent temperature contrast observed with the IR camera for the TMN-46 replica anti-tank mine buried in undistributed soil at the peak contrast during day and night time. The image showing the peak contrast during the day time (left image) was taken at 16:55 and the one showing peak contrast during the night time (right image) was grabbed at 05:25 during the trial of July 5-6, 1993. The trial corresponds to that presented in Figure 3.5. For the left image, the apparent temperature range between a black pixel and a white pixel corresponds to  $3.5^{\circ}\text{C}$ . For the right image, the apparent temperature difference between black and white pixels is  $3^{\circ}\text{C}$ . The circles show the position of the buried mines.

## 4. Discussion

As mentioned in the theoretical section, the thermal characterization of buried mine-like objects is a delicate task. The numerous parameters (sunshine level, air temperature, humidity,...) involved in this thermal behaviour make comparison between distinct 24-hour trials very difficult to perform. Consequently, as a result of the experimental process chosen here (where each 24-hour trial was done with one type of mine and one type of soil), precise comparisons between results with different types of mine or soil are inapplicable. However, following the experimental results presented in this report, general observations for the different mine-soil combinations can be tentatively put forward<sup>1</sup> and temperature contrasts reported give a good estimate of what can be observed in similar situations.

Before presenting the general observations that can be mentioned with reasonable trust from the experimental results found in this report<sup>2</sup>, it is important to differentiate the case of mines buried in undisturbed soil from that of mines buried in disturbed soil. Here we associate mines buried in undisturbed soil to the usual situation where a hole is dug to bury a mine without modifying the surrounding soil (case shown in figure 3.5). On the other hand, mines buried in disturbed soil refers to the case where the soil surrounding the buried mine has been mixed (homogenized) to eliminate the thermal effect created by the hole digging action itself (cases shown in figures 3.1, 3.2, 3.3, 3.4). With this difference stated, general observations about the thermal behaviour of buried mines can be postulated as follow.

### 1. Mines buried in disturbed soil:

- An average maximum thermal contrast equivalent to 2 deg C can be observed.
- No mine-soil combination studied in this report shows observable thermal contrast for a soil layer above the mine greater than 8 cm.
- As expected, the thermal contrast decreases with the depth at which the mine is buried.

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<sup>1</sup>More trials and data acquisitions should be accumulated to confirm statistically these preliminary observations.

<sup>2</sup>It should be mentioned that the observations enumerated here were not only based on the graphs shown in section 3 but also on the visual study of the 48 images taken during each 24-hour trial.

- For some of the 24-hour trials, the thermal contrasts created by the buried mines were observable during night time but not during day time.
- The PM-60 and TMB-D types of mine (see appendix A) seem to show greater thermal contrast than the TMN-46 for the three types of soil studied in this report (a possible explanation for this result is the greater thickness of the PM-60 and TMB-D compared to the TMN-46).
- The experimental measurements described in this report do not show clearly that one type of soil enhances the thermal contrast of buried mines more than any of the two others.

## 2. Mines buried in undisturbed soil:

- An average maximum thermal contrast equivalent to 3 deg C can be observed. This represents an increase of approximately 50% in thermal contrast compared with the results obtained with mines buried in disturbed soil.
- The observed thermal contrasts show little dependency with the depth at which the mine is buried.
- The thermal contrast associated with the holes dug and refilled with and without the mines is comparable.
- A rainfall will considerably reduce the temperature contrast. This can be explained by a temperature homogenization effect at the soil surface by the water. This effect should be the same for the case of mines buried in disturbed soil.

With these observations, an important conclusion to emphasize is that the local perturbations of the physical properties of the soil when a hole is dug and filled with or without a mine in undisturbed soil is largely responsible for the thermal contrast observed. This thermal behaviour of buried mines in undisturbed soil can be explained by considering the local change in density of the soil layer above the mine by the action of digging and refilling a hole<sup>3</sup>. In this situation, a reduction in soil density implies an increase in porosity. Following the theoretical analysis presented in chapter 2, it has been mentioned that the thermal model describing soils has to include the classical thermal conductivity through solid and the latent heat transport by moisture. Consequently, we can reasonably assume for the weather conditions and the prairie soil types used during this trial that the increase in porosity reduces more the thermal conductivity of the soil than it increases its latent heat transport efficiency. As a result, the overall heat drain through the soil is locally reduced which forces the other heat dissipation processes to increase. One of these dissipation processes is the radiative emission (surface emittance) and because the increase of this dissipation process implies a temperature rise, local temperature inhomogeneities will build

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<sup>3</sup>The change in soil density resulting from this operation is well known in civil engineering.

up at the soil surface where holes were dug and filled. From the measurements obtained in this report, these local temperature inhomogeneities are large enough to be observed with commercial IR imagers.

However, an important question which has not been addressed in this report is the duration of these soil thermal inhomogeneities. From the time scale involved during the trial which has produced the experimental data, we can assume that the reported temperature contrasts are valid for at least a week. We can also assume that eventually, with the help of the weather and time, these soil inhomogeneities will disappear. At that moment, the mechanism responsible for the thermal contrast will be related only to the presence of the buried mines, which is equivalent to the cases of the mines buried in disturbed soils presented in this report.

From the preceding discussion, it appears that a passive IR imaging technique should have a reasonable success (close to 100%) for detecting buried mines (metallic or not) for scenarios where four conditions are present: the soil surface to inspect can be observed directly (no grass cover), the whole area of interest is submitted to similar irradiation (shadows from trees or little bumps can cause thermal inhomogeneities), the soil to inspect is naturally compacted <sup>4</sup>, and the mine's burial is sufficiently recent. A potential scenario including these four conditions is the regular inspection of a dirt road for potential buried mine threats.

Finally, an analysis of the detection of buried mines using a thermal imager would not be complete if the problem of false alarm was not discussed. The potential sources of false alarms with this detection technique can be numerous. The apparent temperature recorded by an IR imager is not directly related to real temperature change in the scene observed. This results from the basic operating principle of the IR imager which is to perform a two-dimensional mapping of the amplitude of the incident IR radiation. For an imager based on longwave IR radiation (8-14  $\mu\text{m}$ ), the major portion of the incoming radiation originates directly from bodies at ambient temperature. However, a small change in emissivity (and reflectivity) in a spectrum interval where a non-negligible amount of sun incident radiation is present can significantly change the energy absorbed locally by the soil. This increase of absorbed energy modifies the local thermal equilibrium and contributes to a localized temperature increase. This implies that small local changes in emissivity at the soil surface could produce apparent temperature changes comparable to that created by a buried mine. This small local emissivity change can be created by a dry water hole which has accumulated a layer of small rocks with clay or other local changes in soil type at the surface (gravel patch, sand pit). In most cases, these differences in emissivity can be identified by visual inspection or this effect can be reduced by doing night inspection. Other potential sources of false alarms are when there is the presence of heterogeneous objects buried close to the surface or when a hole was dug and filled without a mine. In both cases, direct mechanical inspections have to be performed. It is certain that a non-negligible false alarm rate will be present in most scenarios. Martin Marietta reports a false alarm rate of less than one

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<sup>4</sup>Sand on a beach is a good example of soil type which is not naturally compacted.

over 20 m<sup>2</sup> [15] (with 100% detection efficiency) with one IR band imager (8-12  $\mu$ m) and neural network image analysis. This false alarm rate corresponds to one false alarm each 5 meters of travel on a 4 meter wide road. A level of false alarm of this magnitude makes this detection technique much less attractive. However, the addition of secondary information tools (metal detector, nuclear detection,...) to this technique should improve this false alarm rate.

## 5. Conclusion

The detection of buried mines is a problem of prime interest internationally. One potential method to succeed in this task is to use passive IR imaging to form thermal images of the soil surface. Even if this technique has been intensively investigated for the last 15 years, few quantitative measurements of the apparent temperature contrast at the soil surface above buried mines have been publicly reported [7, 9]. This document aimed to improve this situation. To help in the interpretation of the results presented, a simple introduction to the thermal mechanisms associated with buried objects has been given. The apparent temperature contrast was measured for different mine-soil combinations over 24-hour periods with a camera sensitive to long wave infrared (8-12  $\mu\text{m}$ ). The effect of the variation in burial depth was investigated and special attention was taken to differentiate the thermal effects associated with the soil disturbance from the mine itself. A maximum average of 2 degrees C in apparent thermal contrast is reported and this apparent thermal contrast disappears when the burial depth exceeds 8 cm for the case where the thermal disturbance is related to the buried mine only. A 50% increase ( $\sim$  3 degrees C) is observed when the thermal effect of the soil disturbance is present. Furthermore, this last apparent thermal contrast shows little dependency with the burial depth. These results are promising for the detection of mines buried in compact soil where the thermal effects of the soil perturbation are not negligible. However, serious reservations should be kept in mind about the false alarm rate which can considerably reduce the effectiveness of this method and the duration of the thermal effects created by the soil disturbance. Further trials should be designed and performed to evaluate this false alarm rate for different scenarios and to evaluate the time dependency of this soil thermal perturbation effect.

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## Appendix A

### Photographs of the Mines Used in this Study

In this appendix, photographs of the three different anti-tank mines used in this study are shown. Their names and the construction materials are specified. For more information, the reader can consult Stuart [16].



Figure A.1: TMN-46 anti-tank mine. Construction material: metal. Origin: Russian.

A.2

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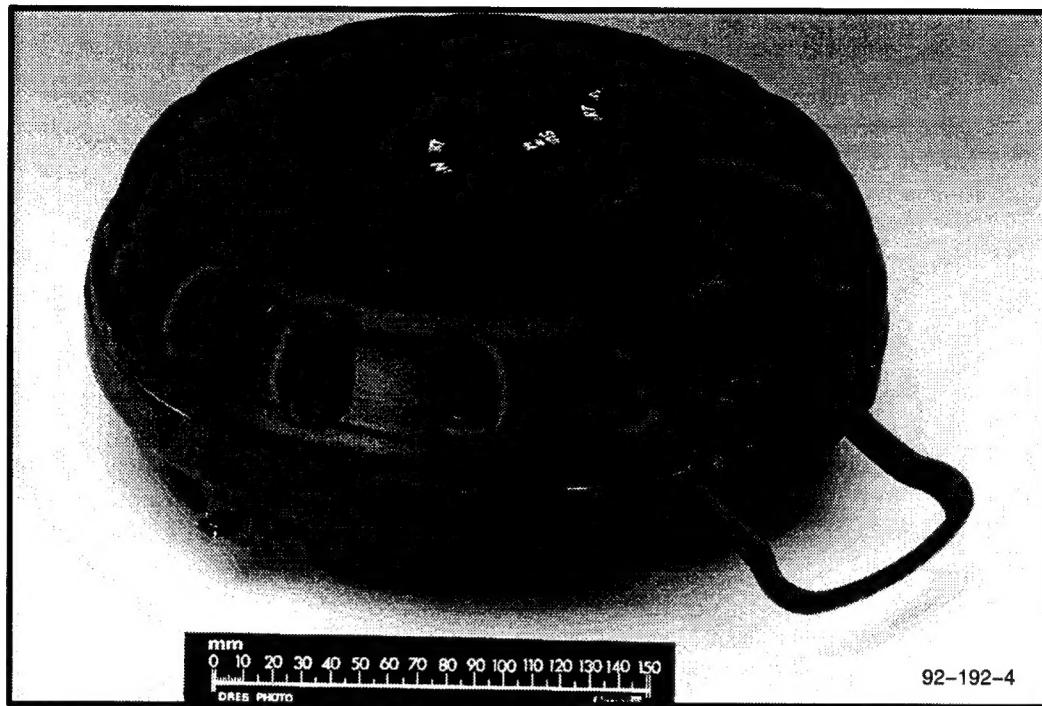


Figure A.2: PM-60 anti-tank mine. Construction material: polymer.  
Origin: former East German

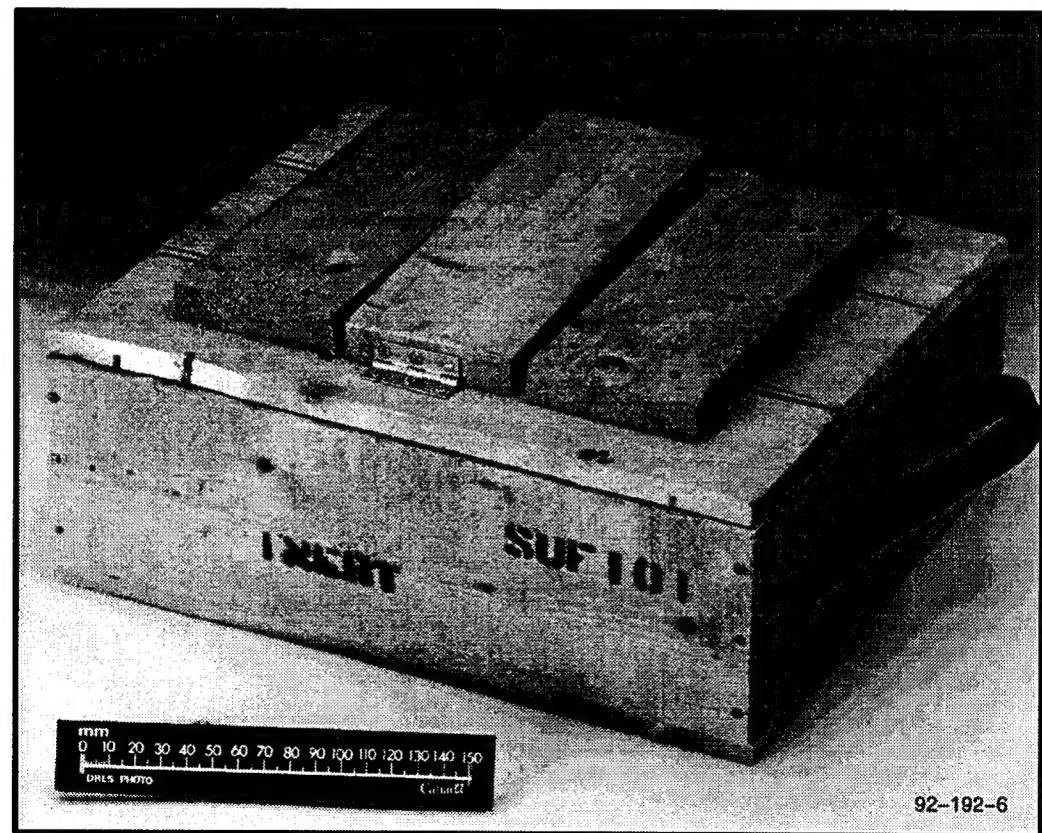


Figure A.3: TMB-D anti-tank mine. Construction material: wood. Origin: Russian.

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The detection of buried mines is a problem of prime interest internationally. One potential method to succeed in this task is to use passive IR imaging to form thermal images of the soil surface. Even though this technique has been intensively investigated for the last 15 years, only few publicly reported studies show quantitative measures of the apparent temperature contrast at the soil surface above buried mines. This document aims to improve this situation. Apparent temperature contrasts are measured for different mine-soil combinations over 24 hour periods with a camera sensitive to long wave infrared (8-12 $\mu$ m). The effect of the variation of burial depth is investigated and special attention is taken to differentiate the thermal effects associated with the soil disturbance from the mine itself. A maximum average of 2 degrees C in apparent thermal contrast is reported and this apparent thermal contrast disappears when the burial depth exceeds 8 cm for the case where the thermal disturbance is related to the buried mine only. A 50% increase (~ 3 degrees C) is observed when the thermal effect of the soil disturbance is present. Furthermore, this last apparent thermal contrast shows little dependency with the burial depth. These results are promising for the detection of mines buried in compacted soil. However, serious reservations about an acceptable false alarm rate and the duration of the thermal effect created by the soil disturbance are expressed.

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